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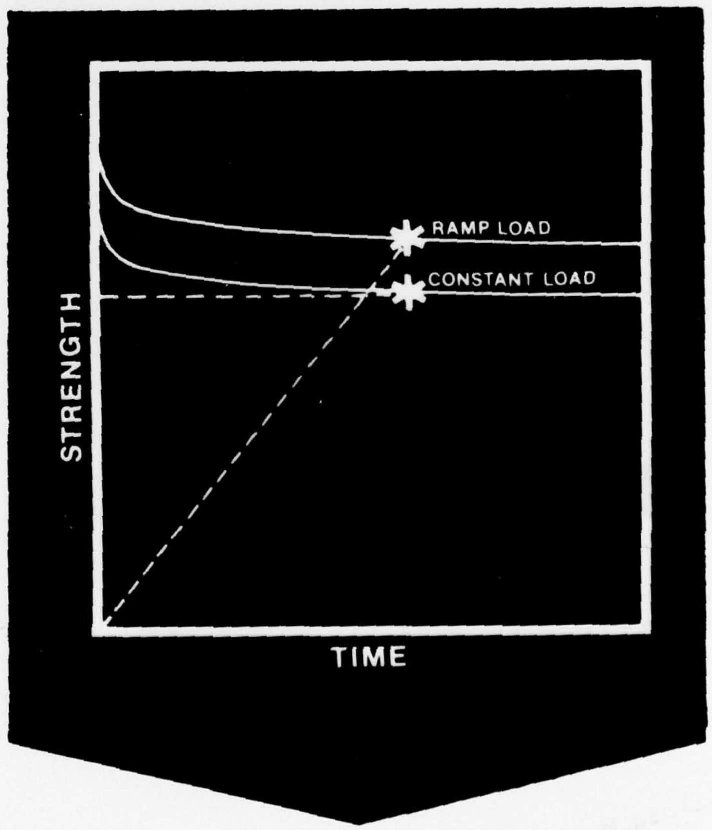

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ABSTRACT

This study reviews world literature on the strength-related effect of duration and rate of loading on wood and wood-based materials. Also, early developments are discussed which led to the currently used permanent loading factor of 9/16. Published data on duration of load are reanalyzed and compared.

The comparisons suggest that the effect of stress level on duration of stress for wood is greater for shear than for bending or compression. The comparisons also suggest that the stress level effect is greater in hardboard, particleboard, and plywood than in solid wood. A similar comparison of loading rate effects suggests that strength is affected to a greater extent in green wood than in dry wood, particularly in bending. For dry wood, the effect of loading rate on strength is most pronounced in tension perpendicular to grain, followed by compression parallel to grain, bending, and shear. Results also suggest that loading rate in bending has a slightly greater effect on hardboard strength and a slightly lesser effect on particleboard strength compared to strength of wood.

The shortcomings of the present data on loading rate and duration are discussed. Suggestions are made for needed research.

EFFECT OF DURATION AND RATE OF LOADING ON STRENGTH OF WOOD AND WOOD-BASED MATERIALS[1]

By

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INTRODUCTION

Several recent publications suggest a renewed interest in the time-related effects of loads on wood strength. Pearson has summarized some of the world literature on wood bending strength as affected by load duration *(31)*.[3] Also, several recent studies by Madsen *(17-20)* have dealt with structural lumber strength as affected by loading rate. Madsen's publications have questioned design procedures accepted since about 1948 *(27)* to account for load-duration effects on wood. Madsen's articles suggest that the relationship between rate and duration of loading is not entirely understood and warrants a fresh look.

This paper summarizes the pertinent world literature on rate and duration of loading for wood and wood-based materials. Several forms of loading are involved including bending, compression, tension, and shear. Creep and relaxation phenomena, however, will not be discussed. This paper also presents some tentative conclusions and suggests some directions for further research.

DURATION OF LOAD FACTOR

Haupt, as early as about 1840, recognized that prolonged loading could affect bending strength of wood *(36)*. The effect was also noted in 1881 by Thurston, who found that small wood beams broke between 8 to 15 months under a load of about 60 percent of short time strength *(36)*. At about the same time, Lanza *(37)* was unable to find any evidence that large beams spanning 20 feet were weakened by 6 months' loading that caused stresses on the order of 1,000 to 1,700 pounds per square inch (lb/in.^{2}). At that time also, Johnson *(37)* was reporting that column strength for longtime duration was only about 50 percent of column strength determined in a testing machine.

In 1908, Tiemann reported that strength of wood increases with rate of loading, with roughly the same increase in compression parallel as in bending for equal fiber strain rates *(37)*. Tiemann also published some tentative conclusions about sustained loading strength of beams *(38)*, including the follow-

[1]Portions of this paper were presented at the 29th Annual Meeting of the Forest Products Research Society, June 17, 1975, in Portland, Oreg.

[2]Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

[3]Numbers in parentheses refer to Literature Cited at the end of this report.

ing: (a) Static strength and stiffness are not affected if sustained stresses below the static elastic limit are removed before any failure occurs; (b) dry longleaf pine beams may be permanently loaded to within 75 percent of the elastic limit provided no increase in dampness occurs; and (c) sustained loads are safe so long as rate of deformation decreases with time.

A duration-of-load factor eventually evolved to account for the sustained load effect. The factor, 9/16, was recognized as the ratio of the elastic limit to the modulus of rupture for wood *(1,11)* in standard strength tests *(2)*. Thus 9/16 was recommended as a dead load factor in determining how strong a piece had to be to have a 1,600 $lb/in.^2$ working stress *(1)*. At least by the 1920's, the factor seems to have been accepted for longtime loading without attaching any specific time limitation *(11,28)*, although working stresses recommended in 1927 were assumed to provide a near-minimum factor of safety of 1.5 under continuous loading of about 10 years *(26)*.

Combs in 1939 thought the 9/16 factor corresponded to about 500 years' sustained loading *(6)*. He extrapolated a load-duration curve presented by Markwardt and Wilson *(21)* that was primarily based on effect of loading rate on wood bending strength. Combs also proposed a curve, based on the extrapolation, which gave 10 years' duration as the basis for comparing strengths for other loading times. As will be seen later, 10-year full design load became known, and is currently known, as "normal loading".

Work of L. W. Wood

During World War II, a comprehensive study was undertaken at Forest Products Laboratory on the effect of sustained load level on the duration of bending load for small clear specimens of wood at 6 and 12 percent moisture content. Based on partial results of that study, Wood in 1947 proposed a curve relating 'percent of normal strength' [here meaning strength as determined by standard test methods *(2)*] to 'duration' *(39)*. The curve passed through 100 percent of the standard test strength at about 5 minutes' duration and by extrapolation, through 56 percent (9/16-factor equivalent) of standard test strength at about 27 years' duration. In 1951, Wood presented a more complete analysis of the duration data which extended to about 10 years *(40)*.

Wood's data and his curve published in 1947 are shown in figure 1. Each data point (fig. 1) is based on a constant stress level (SL) expressed as a percent of two matched control specimens and a time to failure (D) in hours that includes the uploading time (from 0.067 to 0.167 hour depending on the planned stress level) as well as the time sustained at the planned stress level. Analysis of Wood's trend line shown in figure 1 results in the exponential relationship:

$$SL = 90.4 - 6.3 \log_{10} D \qquad (1)$$

It would seem that the duration for permanent loading based on the 9/16 factor should be about 27 years rather than the 500 years proposed by Combs, at least on the basis of Wood's data and his trend line. However, Wood considered that, in addition to the data on sustained loading, the trend of data reported for rapid loading *(15)* should also be reflected in a load-duration curve for wood. The trends for rapid loading and sustained loading are shown in figure 2 along with a hyperbolic curve that Wood thought best fit all of the data. With D as the duration to failure in seconds, the equation of the hyperbolic curve as given by Wood is

$$SL = \frac{108.4}{D^{0.04635}} + 18.03 \qquad (2)$$

When stress level is 56.25 percent (9/16 equivalent), equation (2) yields a "permanent load" duration of about 216 years. Equation (2) also allows that a stress level of 18.3 percent can be sustained forever. The hyperbolic curve has somewhat the same shape as that proposed earlier by Combs, but Wood's curve is everywhere steeper.

The Concept of 'Normal Loading'

When Wood published his load-duration curve, the allowable properties for wood in bending, tension, compression, and shear were then tied to a 'normal loading' condition rather than to permanent loading. The idea of normal loading was first introduced into the National Design Specification [early edition of ref. *(25)*] in 1948 along with suggested increases in allowable properties for other specific durations of loads. The revision also made allowable stresses for permanent loading 90 percent of those allowable for normal loading.

The 1948 NDS revision did not define lengths of time associated with either normal loading or permanent loading. In the 1950 revision of NDS, however, the normal load duration was stated to be about 3 years, either continuously or cumulatively, at the full maximum allowable stress "and/or" 90 percent of that stress continuously for the remaining life of the structure. The 3 years' duration for normal loading was changed to 10 years' duration in the 1951 NDS revision. The 1952 NDS revision added a load-duration curve based on Wood's hyperbolic curve [eq. (2)] *without any substantive revisions in load* duration concepts. The NDS load-duration curve was not limited to allowable bending stress but was captioned as applying to *all* of the allowable strength properties. The 1952 concepts have been retained in the present NDS.

In retrospect it would seem that constant loading effects should have been treated independently of rate of loading effects because the two phenomena involve different loading conditions. When treated independently, the experimental evidence available in the world literature tends to support the exponential form

$$SL = A + B \log_{10} D \tag{3}$$

for relating constant stress level, SL, to the time, D, to failure. Evidence in the world literature also supports the exponential form

$$USL = M + N \log_{10} T \tag{4}$$

for relating the ultimate stress level, USL, to the time, T, required to attain ultimate at some rate of loading. SL and USL are relative values, based on the strength of controls or the estimated strength for a 5-minute static strength test.

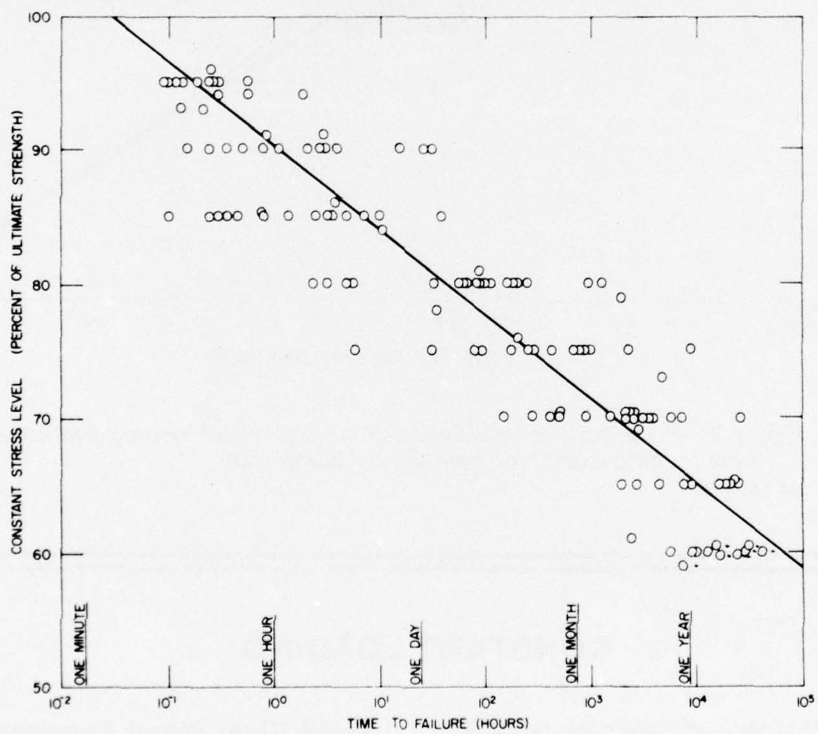

Figure 1.--Constant bending load-duration data by Wood (40).
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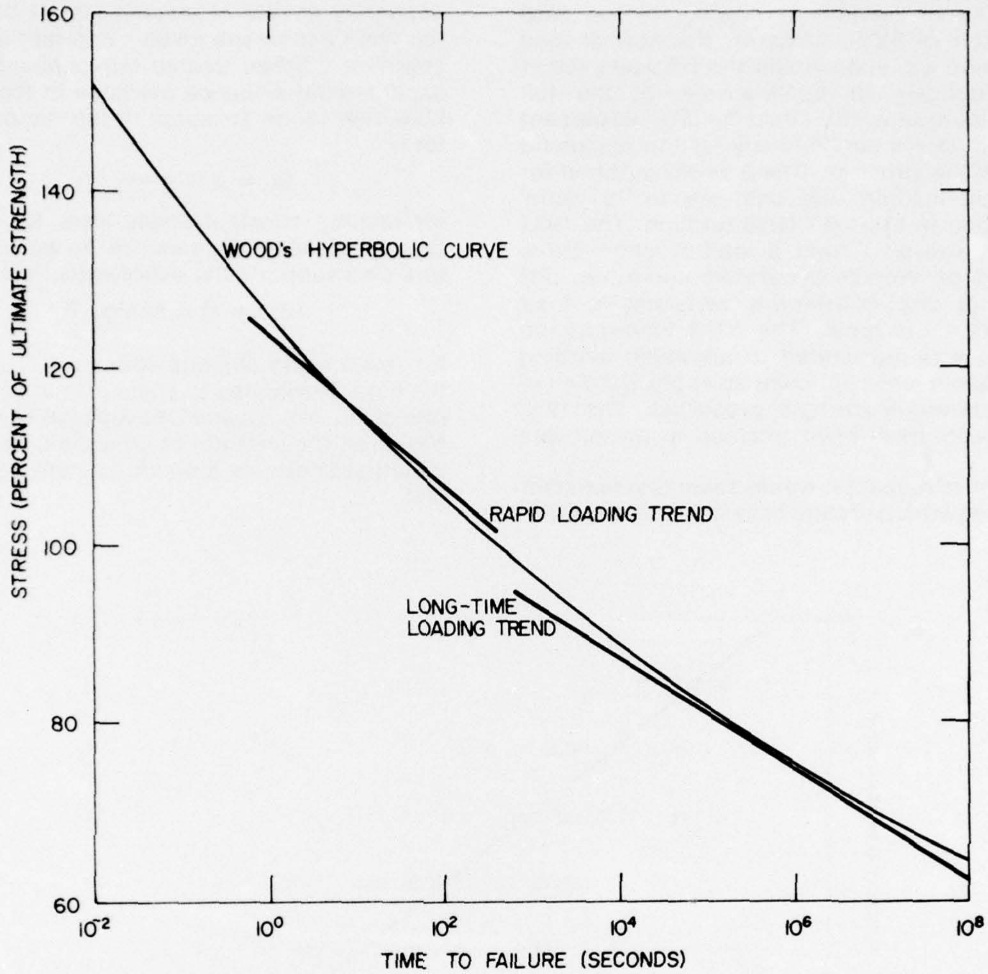

Figure 2.--Hyperbolic load-duration curve with rapid loading and long-time loading trends for bending by Wood (40).
(M 143 499)

CONSTANT LOADING

Several other studies have been reported in the world literature on constant load duration for wood and wood-based materials. In general, the studies are less comprehensive than Wood's. The studies involve small clear specimens of wood, laminated wood, plywood, hardboard, and particleboard.

Small Clear Wood Specimens

Youngs and Hilbrand *(41)* reported load-duration data for wood bending specimens subjected to cyclic stress-no stress loading of long duration; a pair of control specimens was used to establish the stress level for each long-time loading specimen. For comparable stress levels, Youngs and Hilbrand found that the duration of applied stress--that is, accumulated time under actual stress--agreed with Wood's sustained loading data. Schniewind *(32)* also reported conforming data for sustained bending loads. Schniewind based his sustained loads on a relation between modulus of rupture and the two variables--modulus of elasticity and weight of control specimens.

Brokaw and Foster *(4)* conducted duration tests at high stress levels in both bending and compression parallel to grain, up to about 125 percent of static strength of matched controls. Many of the reported durations for the constant loading portion of stress, however, were as short or considerably shorter than loading time to stress level, even though loading times were very short--under 3 seconds. Because of the relatively short durations of constant load to failure, the data are difficult to interpret on the same comparative basis of other data reviewed. Most of the Brokaw and Foster data in compression up to and including the 105 percent stress level appear to have sufficiently long durations for establishing a load-duration trend; however, their data in bending are somewhat less suitable because durations reported were more variable and relatively short compared to loading times.

Several other reports on constant loading for clear wood specimens have appeared in the world literature:

Leont'ev (13): Reported on some constant load-duration data in shear along with a range in moisture content suggesting no special climatic control.

Sugiyama (35): Reported some limited constant loading data for cantilever bending specimens subjected to natural ventilation.

Schniewind and Centeno (33): Conducted constant loading tests in bending with grain oriented perpendicular to the usual alinement. Specimens used in these bending tests contained notches.

Bach (3): Also conducted constant loading tests in bending with grain oriented perpendicular to the usual alinement, but without notches. In another study,[4] Bach reported constant loading data in tension parallel to grain for a limited number of maple specimens. These specimens failed in a creep study under

[4]Bach, L. 1965. Nonlinear Mechanical Behavior of Wood in Longitudinal Tension. Doctoral diss. Syracuse Univ., N.Y.

Table 1. -- Coefficients in SL = A + B $\log_{10}$D with related data -- small clear wood specimens under constant load[1]

Item No.	Reference No.	Type of test	Approximate number of specimens	Species	Moisture content	Coefficients[2] A	Coefficients[2] B	Predicted duration at 100 percent SL	Predicted SL at 10 years
					Pct			Min	Pct
1	Wood *(40)*	Bending	126	Douglas-fir	6, 12	90.4	-6.3	1.8	59
2	Youngs *(41)*	...........do...........	13	.........do..........	6, 12	90.4	-6.3	1.8	59
3	Schniewind *(32)*	...........do...........	64	.........do..........	12	90.4	-6.3	1.8	59
4	Brokaw *(4)*	Compression parallel	163	Sitka spruce	12	*82.2	*-6.7	.13	49
5	Brokaw *(4)*	Bending	197	..........do.........	12	*83.7	*-7.4	.38	47
6	Leont'ev *(13)*	Shear	30	Spruce	10-16	91.4	-10.4	8.9	40
7	Sugiyama *(35)*	Bending	22	Cryptomeria	(3)	90.0	-8.9	4.5	46
8	Schniewind *(33)*	Bending perpendicular, with notch	76	Douglas-fir	12	89.0	-7.3	1.9	53

[1]SL in percent and D in hours.

[2]Coefficients A and B based on curve, or equation presented in reference, except for items with *, which were determined by Gerhards.

[3]Experiment conducted with "natural ventilation."

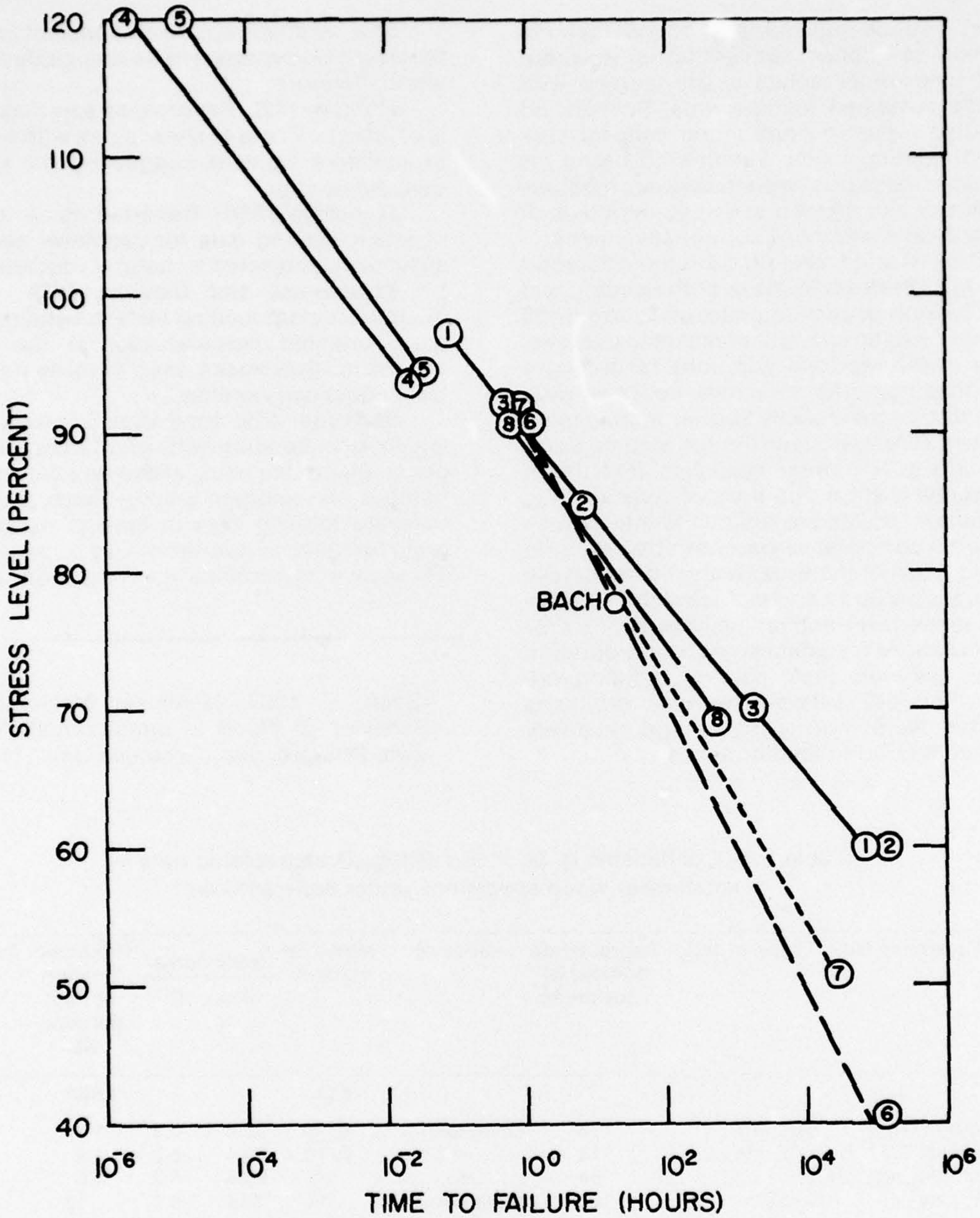

Figure 3.--Constant load-duration relationships based on small clear wood specimens, including a single point estimate after Bach. (Numbers refer to itemized data in table 1.)

1,2,3,5,7--bending

4--compression parallel

6--shear

8--bending perpendicular

(M 143 494)

various constant temperature-humidity conditions at one stress level; Bach estimated a 50 percent survival of 1,000 minutes at the 78 percent stress level.

A group of controls was apparently used within each of the four studies *(3, 13, 33, 35)* to set the desired sustained stress levels, with Bach adjusting the common base for moisture content and temperature.

Pertinent data based on results given in studies on constant load duration for wood, referenced above, are summarized in table 1, using the form of equation (3) as a basis. Except for items 4 and 5 of table 1, the A and B coefficients for equation (3) are either based on equations or on graphed lines presented by authors. The first three items in table 1 have common coefficients because Youngs and Hilbrand and then Schniewind chose to use Wood's trend line for comparison with their data. Brokaw and Foster (items 4 and 5) originally fit their data for compression and bending with exponentials that included uploading time as well as duration under constant load; consequently, the A and B coefficients given in table 1 are a recalculation of their data, excluding loading times. Bach's bending perpendicular results are not included. His results are difficult to interpret because of a large variation in times to failure, truncated tests at lower stresses, and failures during uploading to high stresses.

Figure 3 shows graphs of the equations based on the eight sets of coefficients given in table 1, and also shows Bach's single-point tensile strength estimate. The curves in figure 3 are identified by itemized numbers from table 1 and are limited to the range of stress levels reported in each source of data. While several of the curves agree relatively closely at about the 90 percent stress level, agreement is poor at low stress levels, perhaps because of property, species, or test condition differences.

The credibility of the equations represented by the A and B coefficients given in table 1 can be evaluated by the durations predicted for SL = 100 percent. Estimates predicted by the equations for the 100 percent stress level are shown in minutes in the next to last column of table 1. The estimates vary from about one-tenth of a minute to about 9 minutes. For reference, a standard static test specimen is loaded at some nominal rate to cause failure in about 5 minutes *(40)* and only attains the ultimate load just prior to or at failure. Therefore, a specimen loaded rapidly to 100 percent stress level should only be able to carry that stress level for a short time--considerably less than the static test time. Thus, the longer durations (4 1/2 and 9 min) appear excessive. The two equations based on durations at very high stress levels reported by Brokaw and Foster *(4)* suggest a 100 percent stress level duration of about one-quarter minute, whereas Wood's trend line suggests about 2 minutes.

Perhaps a better estimate of the 100 percent stress level duration can be obtained by combining Brokaw and Foster's data on bending with Wood's data. Figure 4 shows a plot containing the two sets of data. Brokaw and Foster's data on Sitka spruce were copied from a figure of plotted data [*(4)*, fig. 6]. Wood's data for times under constant load on Douglas-fir were obtained from his original notes because his duration data published in *(40)* did not separate uploading time from the time under constant load. The two sets of data, even though for different species, seem to be reasonably related. Figure 4 data also show the final outcome for specimens tested at the 60 percent level which had not failed when Wood presented his results. Figure 4 is oriented with duration as the ordinate and stress level as the abscissa to emphasize that duration is the response to imposed stress. (The orientation used by Wood and others does not clearly indicate duration as a response to stress.)

Two lines are shown passing through the data of figure 4. The upper line is Wood's trend [eq. (1)] expressed with D in seconds. The lower line represents my interpretation of all of the data from about 105 percent stress level on down, also with D in seconds. Times to failure for stress levels above 105 percent tend to be short relative to loading time to stress level. These times to failure also show apparent bias because the minimum duration appears to be about 0.03 second regardless of stress level. In equation form with D in hours, the lower line is the exponential

$$SL = 87.8 - 5.8 \log_{10} D \qquad (5)$$

Equation (5) predicts a duration of about 28 seconds at 100 percent stress level.

The estimated stress level for 10 years' duration (normal loading) is also of interest. Estimated stress levels predicted by the curves in figure 3 for 10 years' duration are shown in the last column of table 1. The estimates range from 40 to 59 percent. Equation (5) predicts 59 percent. The lowest stress level estimates (40 and 46 pct) may be due to fluctuating specimen moisture contents as tests were apparently conducted under uncontrolled humidity conditions. Creep-rupture in small specimens

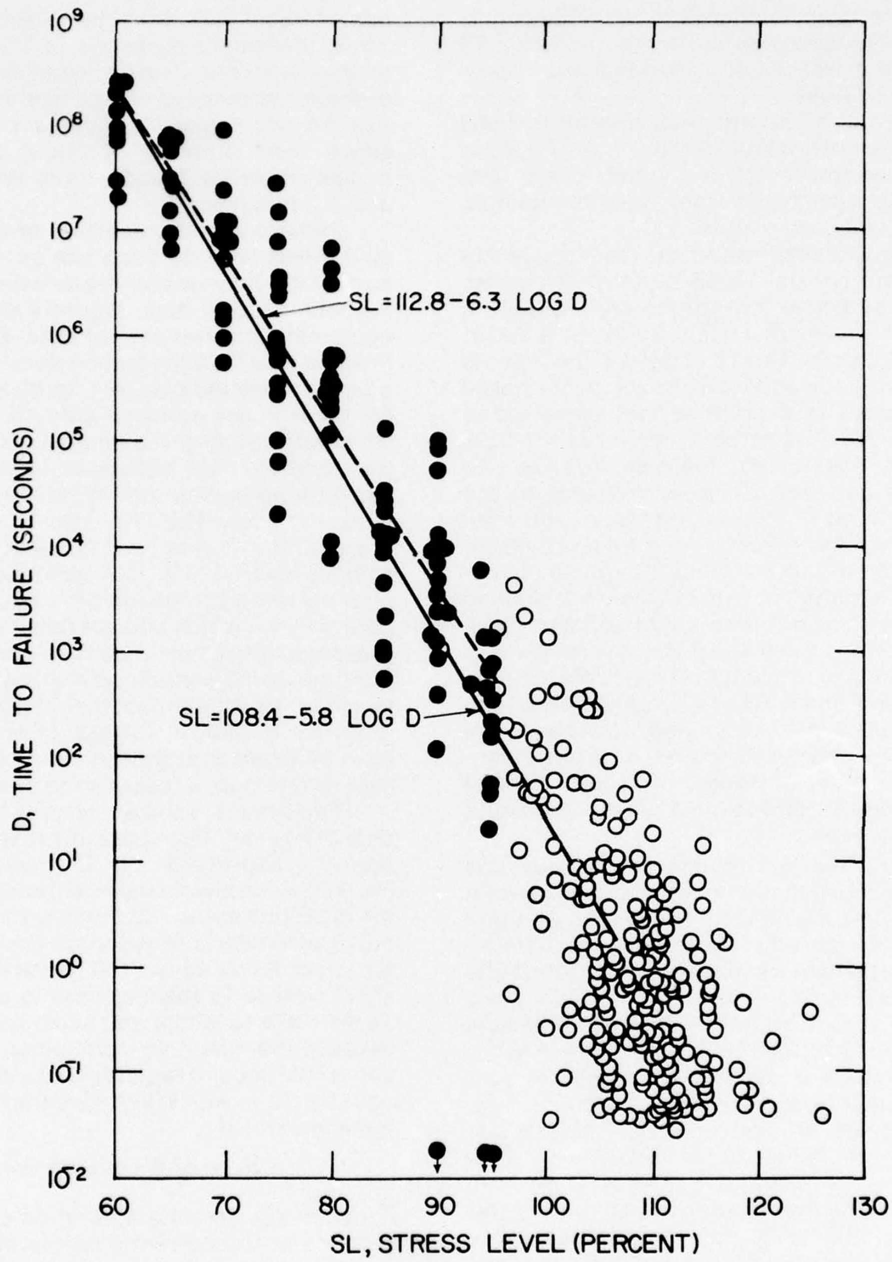

Figure 4.--Constant bending load-duration data from Brokaw and Foster and from Wood (o--Brokaw and Foster; ●--Wood) Downward-pointing arrow indicates failure during loading.

(M 143 498)

is known to occur at a faster rate in a fluctuating moisture environment than in an unchanging moisture environment *(32)*. The highest stress levels for 10 years' duration are based on tests at constant moisture contents.

Wood-based Materials

Besides the data based on small clear specimens of wood, constant load-duration results have also been reported for particleboard, hardboard, plywood, and laminated wood beams.

Particleboard.--Bryan *(5)*, Kufner *(12)*, and McNatt *(23)* reported long-duration data for particleboard in bending or tension. Bryan tested four types of particleboard; he established stress levels for the constant-load bending specimens based on the average strength of a set of control specimens for each board type. Kufner tested bending specimens representing eight types of particleboard at several different levels of constant stress, but also reported average strength of controls for each type of board. McNatt loaded tension-parallel-to-surface specimens representing four different particleboards at constant stress levels. These stress levels were based on a set of control specimens for each board type.

Hardboard.--McNatt *(22)* and Haygreen and Sauer *(7)* presented constant-load-duration data for hardboard. McNatt's data are based on tension-parallel-to-surface specimens from three different tempered hardboards; a set of control specimens from each board type was used to establish stress levels. Haygreen and Sauer's data are based on bending tests of two different types of hardboard for two different atmospheric conditions. Haygreen and Sauer reported average constant load-durations for several different applied stresses along with exponential stress-duration equations and average static strength for comparable specimens.

Plywood.--Mohler and Ehlbeck *(24)* presented constant load-duration data for several types of plywood in bending, along with average strength of comparable control specimens.

Laminated beams.--Littleford *(16)* subjected laminated beams to constant loading at several levels of stress. He first based stress level on average static strength of similiar control beams but abandoned that approach due to large variability in the constant load-duration data. In Littleford's second approach, he used a regression of modulus of rupture on the product of two variables--modulus of elasticity and deflection at failure of controls--to predict an ultimate strength for each sustained loading beam. The estimated ultimate strengths were used to estimate stress levels for the constant loading beams.

Most of the data presented in this group of references for wood-based materials have needed reanalyzing here to conform to equation (3). Bryan, Kufner, Mohler and Ehlbeck, and Littleford presented regressions of stress or stress level as the dependent variable on logarithm of duration as the independent variable. Actually the duration for a specimen under constant load is the specimen response to the constant load. Therefore, the data from the above four sources were reanalyzed with the logarithm of duration as the regression dependent variable and stress or stress level as the independent variable. Only a part of Kufner's results could be reanalyzed because he did not present a complete set of sustained loading data. McNatt's hardboard data also had to be reanalyzed because his original exponential equation was based on average duration rather than the average log-duration used for his particleboard data. The resulting regression coefficients for those studies reporting applied stress were transposed to the form of equation (3) to conform with others on a stress level basis. The equation (3) type coefficients and related data for wood-based materials are summarized in table 2.

Durations predicted for the 100 percent stress level (table 2) are quite variable and cover a much larger range than durations given in table 1 for small clear wood specimens. The predicted stress levels for 10 years' duration, however, cover about the same range, with similar absolute values in both tables. The 28-minute duration predicted at the 100 percent stress level for laminated beams is unreasonably long and may have resulted from poor estimates of static strength of the beams tested under constant load.

The equations represented by the coefficients in table 2 are displayed graphically in figure 5 along with equation (5) (the dashed line) for reference. There seems to be poor agreement among the curves plotted in figure 5 for any stress level. Although some lack of agreement may be due to material differences, the poor agreement may be largely caused by different effective loading rates for the control specimens. For example, time to maximum load for standard static tension test of 1/4-inch tempered hardboard averaged about 61 seconds in McNatt's study *(22)*, a value about one-fifth of that for the standard static strength test

Table 2.--Coefficients in SL = A + B $\log_{10}$ with related data--particleboard, hardboard, plywood, and laminated beams under constant load[1]

Item No.	Reference No.	Type of test	Approximate number of specimens	Material	Moisture conditioning		Coefficients		Predicted duration at 100 percent SL	Predicted SL at 10 years
					Temperature	Relative humidity	A	B		
					° F	Pct			Min	Pct
A	Bryan *(5)*	Bending	64	Particleboard	72	30	84.3	-6.5	0.23	52
B1	McNatt *(22)*	Tension parallel to surface	68	Hardboard	75	50	78.5	-7.5	.08	41
B2	McNatt *(23)*	.....do.....	44	Particleboard	75	50	84.8	-8.3	.88	44
C1	Haygreen*(7)*	Bending	[2]66	Hardboard	72	72	89.3	-8.6	3.4	47
C2	Haygreen*(7)*	.....do.....	[3]24	.........do.........	72	42	86.7	-5.3	.19	61
C3	Haygreen*(7)*	.....do.....	[4]24	.........do.........	72	42	80.6	-6.3	.05	49
D	Littleford *(16)*	.....do.....	[5]28	Laminated beams	(6)		97.5	-7.7	28.0	59
E1	Kufner *(12)*	.....do.....	30	Particleboard parallel	(6)		85.9	-9.3	1.8	40
E2	Kufner *(12)*	.....do.....	30	Particleboard perpendicular	(6)		76.3	-6.8	.02	43
G1	Mohler *(24)*	.....do.....	31	8 mm beech plywood	68	65	72.9	-5.8	.001	44
G2	Mohler *(24)*	.....do.....	26	16 mm beech plywood	68	65	79.4	-7.2	.08	44
G3	Mohler *(24)*	....do.....	78	8 and 16 mm macore and 12 mm *limba* plywood	68	65	91.5	-7.1	3.8	56

[1]SL in percent and D in hours.

[2]Wet- and dry-processed hardboard combined.

[3]Dry-processed hardboard.

[4]Wet-processed hardboard.

[5]Includes 10 beams which were statically tested after sustaining load for 10,000 h without failure.

[6]Specimen moisture contents ranged between 10 and 12 pct.

for wood. The more rapid rate of loading for the hardboard control specimens caused a higher effective control strength compared to the standard strength for wood. This results in a higher effective stress level for the hardboard specimens under constant loading than for wood specimens under constant loading, even though common stress levels may be claimed.

In other words, if control strengths are not determined at the same relative rate of loading, then stress levels are not exactly comparable and durations for constant loading would not be equal either. For a given claimed stress level, the durations for specimens under constant loading should be shorter for hardboard than for wood, and that is generally what figure 5 shows.

Common Basis Comparisons

For meaningful duration comparisons, the effective loading rate for control specimens should be common among all materials. Because control data do not seem to be compar-

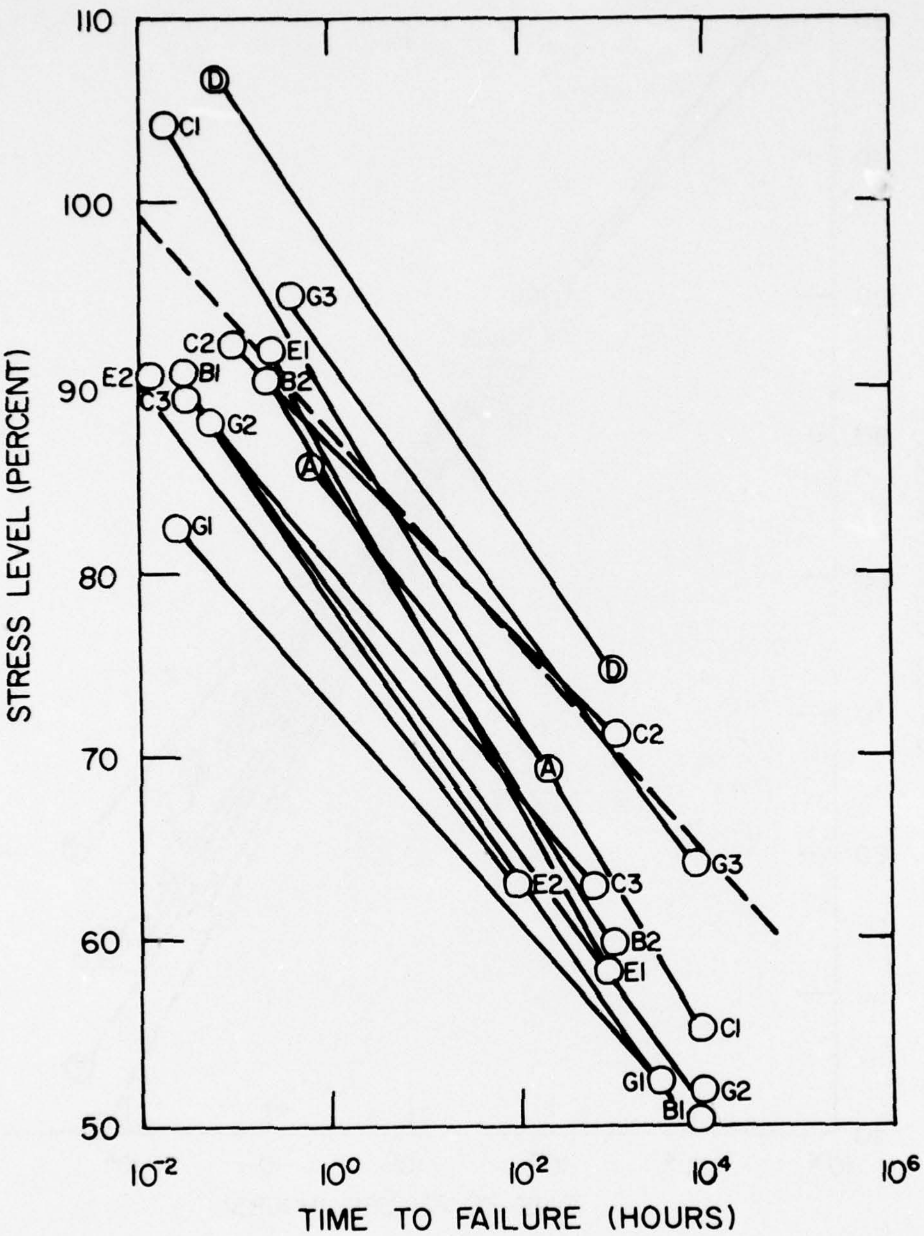

Figure 5.--Constant load-duration relationships for hardboard, plywood, particleboard, and laminated wood. (Designations refer to itemized data in table 2; dashed line is curve 1 from fig. 3 for reference.)

A,E1,E2--particleboard, bending *C1,C2,C3--hardboard, bending*
B2--particleboard, tension *B1--hardboard, tension*
D--laminated beams, bending *G1,G2,G3--plywood, bending*

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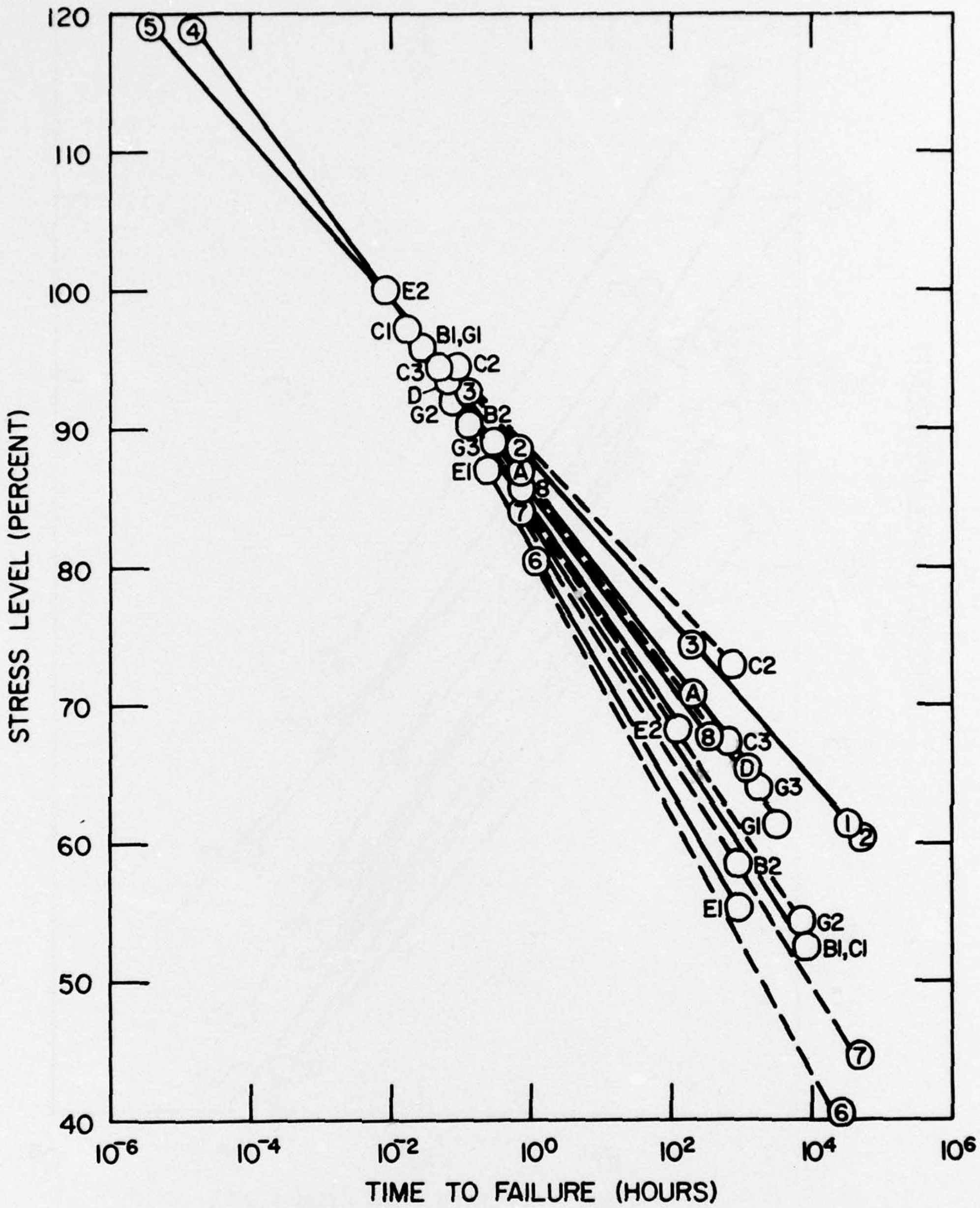

Figure 6.--Constant load-duration relationships for wood and wood-based materials with 28 seconds used as the basis for 100 percent stress level.

1,2,3,5,7--wood, bending	*6--wood, shear*
4--wood, compression parallel	*8--wood, bending perpendicular*
A,E1,E2--particleboard, bending	*C1,C2, C3, hardboard, bending*
B2--particleboard, tension	*B1--hardboard, tension*
D--laminated beams, bending	*G1,G2,G3--plywood, bending*

(M 143 493)

able, the equations represented by the coefficients in table 2 should be adjusted to a common base. In this paper the common base is chosen as 28 seconds at 100 percent stress level. The adjustment to the common base involves calculating the stress level for 28 seconds' duration from the equations represented by the coefficients given in tables 1 and 2, and then dividing the coefficients by that stress level to obtain the adjusted coefficients. Table 3 lists the adjusted coefficients ordered by B for all items given in tables 1 and 2; figure 6 shows the resultant curves.

By comparing figures 3, 4, and 6, it is obvious that much of the variation in the duration relationships has been removed by the common basis adjustment. Figure 6 suggests four groupings: (1) Curves C2 and 5 and the common curve for 1, 2, and 3; (2) curves A, C3, D, G3, G1, 4, and 8; (3) curves E2, G2, B1, C1, 7, and B2; and (4) curves E1 and 6. (As a point of reference, an approximate evaluation of Bach's bending perpendicular data *(3)* suggests a fifth group with $A \approx 75$ and $B \approx -12$.)

Based on the adjusted curves, duration has a greater effect on shear strength (curve 6) than on bending (curve 1) or compressive strength (curve 4) of solid wood. With the lone exception for hardboard (curve C2), bending strengths of hardboard, particleboard, plywood, and laminated wood seem to be affected more by duration than the bending strength of solid wood. The tensile strengths of hardboard and particleboard are also affected more by duration than bending strength of solid wood. The greater effect in laminated beams may have been artificially generated by the method, already mentioned, of estimating the stress level for each beam. However, it is possible that slope of grain due to spiral grain and knots could also account for some of the greater effect.

Table 3.--Coefficients in $SL = A + B \log_{10} D$ from Tables 1 and 2 adjusted to approximately 28-second-100 percent stress level basis[1]

Items	A	B
C2	88.6	-5.4
[2]1, 2, 3, 5	87.8	-5.8
A	86.0	-6.6
C3, D, G3	85.9	-6.7
G1	85.6	-6.8
4, 8	85.3	-7.0
E2	84.2	-7.5
G2	83.9	-7.6
B1	83.2	-7.9
C1	83.1	-8.0
B2	82.9	-8.1
7	82.7	-8.2
E1	81.4	-8.8
6	80.6	-9.2

[1]SL in percent and D in hours.

[2]Based on equation (5)

RATE OF LOADING

The term "rate of loading" implies a constant rate of increase in load or stress, as in pounds per minute, whereas 'rate of deformation' implies a constant rate of increase in deflection, contraction, extension, or strain. 'Ramp loading' usually implies a constant rate of increase in load, but the common practice in wood research has been to refer to rate of deformation or ramp deformation as rate of loading. In this paper both ramp loading and ramp deformation will generally be referred to as rate of loading. (Almost all of the literature dealing with rate effects on wood is based on ramp deformation.)

Small Clear Wood and Structural Sized Specimens

The early work of Tiemann *(37)* on rate of loading has already been discussed. Markwardt and Wilson *(21)* also published on loading rate of Sitka spruce in bending. Results from *(21)* can be interpreted to have the exponential trend given by equation (4).

In addition to these early studies, a number of recent reports have been published on loading rate for wood specimens:

James (8,9): Compared wood bending strength at two nominal rates of loading: (1) Standard static speed and (2) about 10,000 times faster than standard static speed. Overall, James' results suggested an increase in bending strength of 47 percent for green wood and 32 percent for air-dry wood due to the more rapid rate.

Keeton (10): Conducted tests on green and dry wood in bending, compression, and shear. These tests were performed at various rapid loading rates as well as at standard static speed. Except for the air-dry bending tests, Keeton's results generally suggest that ultimate strength increases with loading rate. However, ultimate strength and rate did not seem to be exponentially related.

Okuyama and Asano (30): Related parallel-to-grain compressive strength of buna linearly to the logarithm of strain rate. Strain rates ranged from the standard static rate to about 100 times standard.

Noren (29): Studied the effect of deformation rate on parallel-to-grain compressive strength of Swedish fir. In this study, compressive strength was related to rate of deformation by an exponential.

Strickler and Pellerin (34): Studied the influence of loading rates on parallel-to-grain tensile strength of clear wood having cross sections of about 0.07 and 2.5 square inches without finding a significant rate of loading effect. Loading rates for the larger sized specimens ranged between 20 and 880 pounds per square inch per second, a somewhat limited range compared to other rates-of-loading studies. Rates for the smaller sized specimens ranged between 0.005 and 5 inches of crosshead movement per minute. Strickler and Pellerin indicated that many smaller tension specimens failed in shear through the grip section rather than in tension. Due to the limited range in loading rates for their larger specimens and the failure modes in their smaller specimens, Strickler and Pellerin's results will not be compared with the results for other properties.

Madsen (17-20): Conducted a series of slow rates of stepwise-ramp loading studies rather than the rapid rates of loading used in the other studies reported here. (In stepwise-ramp loading, the load on a specimen is increased incrementally at specified time intervals.) Tests reported in *(17-20)* involved bending, shear, and perpendicular-to-grain tension. Six different rates of loading were used for each type of test. Tests included green and dry 2 by 6 lumber in bending, torque-tube shear specimens from dry lumber, and tension perpendicular to grain specimens from dry laminated beams. Each type of test included clear material as well as material normally included in the category of structural lumber.

The results of the rate-of-loading studies just enumerated are not readily comparable. Markwardt and Wilson, and Liska reported their results in the form of ultimate stress level and time to failure. The results of James, Keeton, Noren, and Okuyama and Asano were given in the form of stress or relative stress and rate of deformation. Madsen reported his results in the form of average ultimate stess and rate of loading.

Because of the diverse forms of results reported, most data needed reanalysis to conform to a common model. The exponential equation (4) is used here as the common model because of its similarity to the constant load-duration equation (3). Each set of M and N coefficients have also been adjusted so that the models all yield 100 percent ultimate stress level in 5 minutes. Because Liska reported M and N coefficients for his data, his equation could be used directly except that those for bending needed to be adjusted to 5 minutes to 100 percent USL. A set of coefficients was estimated directly from the data presented by Markwardt and Wilson.

For Madsen's data, it was necessary to first regress his average ultimate strength data, US, on rate of loading, K, to determine C and D in

$$US = C + D \log K$$

The ultimate stress, US_5, that corresponded to time to ultimate, T, of 5 minutes was determined using the regression and the relation that US = KT. By substituting US/T for K, the regression can be written

$$US = C - D \log T + D \log US$$

Then, M and N were determined for each of Madsen's sets of data by dividing both sides of the equation by US_5,

$$USL = \frac{US}{US_5} = \frac{C - D \log T + D \log US}{US_5}$$

$$USL = M - N \log T + N \log US$$

where M equals C divided by US_5 and N equals D divided by US_5. The quantity N log US turned out to be small compared to values of USL over the range of data reported and so is ignored here.

For the remaining studies, those reporting rates of deformation, the calculations of equation (4) coefficients were based on the assumption that deformation at ultimate stress was independent of deformation rate. Because James' and Keeton's data included the standard static test condition as one of the rates, it was possible to determine the M and N coefficients using the static ultimate strength value, assumed as a 5-minute test to ultimate, as the base.

From Noren's regression data and the static ultimate strength value corresponding to 3.9 minutes to ultimate, the 5-minute ultimate stress value for calculating the M and N coefficients of equation (4) was determined to be 466.5 kilograms per square centimeter (kg/cm_2). The Okuyama and Asano data required a slightly different approach because static strength values were not provided; the average strain at the ultimate stress, however, was reported as 1.35 percent. Based on that strain, the Okuyama and Asano stress-strain rate regression equation, and the ASTM strain rate of 0.3 percent per minute for static testing for compression-parallel-to-grain strength (2), the 5 minutes to ultimate strength was determined to be 479.3 kg/cm^2, which was used as the base for determining M and N.

Table 4 presents the results of the reanalyses of the above referenced rate of loading data. Reanalyses were based on the common model USL = M + N log T with USL in percent and T in seconds in accordance with average trends of reported data. All results except for some of those reported by Keeton fit the common model. In Keeton's report only the green bending specimen data fit the model at all of the rates of loading; data for other modes of loading or for dry specimens tended to deviate from the model at the higher rates of loading. Consequently, the coefficients listed for Keeton's data represent all of his testing speeds for green bending specimens but only half those for his other tests.

The equations represented by the data in table 4 are displayed graphically in figure 7 where the curve numbers correspond to the item numbers of table 4. The lines have been adjusted to all focus on the 100 percent USL-5-minute point. The lines extend over the range of reported data (or useful data in the case of Keeton), except that Markwardt's and Wilson's data extend to about the 90-percent stress level and Madsen's, the dashed lines, generally extend back to 1 minute's duration.

Figure 7 suggests that the effect of loading rate on ultimate stress level varied considerably among the sources of data. Part of this variation seems to be associated with moisture condition, type of test, and, to a limited extent, to size or quality of specimen material.

Regarding moisture condition, almost all of the studies having comparable green and dry wood tests resulted in the greater relative effect of rate in green wood. This may be seen by comparing figure 7 slopes: Curve 22 with curve 23, 25 with 26, and 27 with 28, although the difference in slopes of curves 25 and 26 is only slight. The first-named curve of each pair is for green wood and has the steeper slope. The pair of curves numbered 29 and 31 suggests the opposite, with the rate effect slightly higher in dry than in green lumber. This lone exception may be somewhat questionable, however, as Madsen reported average moisture contents for the 2 by 6 No. 2 bending specimens to range between 7 and 13 percent, with the higher moisture contents associated with the two most rapid rates of loading. What effect these basic differences in moisture content may have had on ultimate load is not known.

Table 4.--Coefficients in USL = M + N log T with related data--small clear and structural sizes of wood under rate of loading[1,2]

Item No.	Reference No.	Type of test	Approximate number of specimens	Species	Moisture condition	Coefficients[3] M	Coefficients[3] N
					Pct		
19	Noren *(29)*	Compression parallel	288	Swedish fir	13	118	-7.1
20	Liska *(15)*	....do....	289	(4)	11	121	-8.5
21	Liska *(15)*	Bending	348	(4)	11	118	-7.3
22	James *(8,9)*	....do....	178	(5)	Green	129	-11.8
23	James *(8,9)*	....do....	178	(5)	14	120	-7.9
24	Okuyama *(30)*	Compression parallel	20	Buna	--	121	-8.3
25	Keeton *(10)*	Compression parallel and shear	160	Douglas-fir	Green	119	-7.6
26	Keeton *(10)*	....do....	160	....do....	Dry	117	-6.8
27	Keeton *(10)*	Bending	160	....do....	Green	125	-10.1
28	Keeton *(10)*	....do....	80	....do....	12	112	-4.9
29	Madsen *(17)*	....do....	225	No. 2 hem-fir 2 x 6	(6)	114	-5.5
30	Madsen *(17)*	....do....	143	Clear hem-fir 2 x 6	7	111	-4.5
31	Madsen *(18)*	....do....	207	No. 2 hem-fir 2 x 6	Green	112	-5.0
32	Madsen *(19)*	Shear	89	Douglas-fir clear	Dry	116	-6.3
33	Madsen *(19)*	....do....	180	No. 2 Construction Douglas-fir	....do....	111	-4.4
34	Madsen *(20)*	Tension perpendicular	76	Clear wood	....do....	128	-11.2
35	Madsen *(20)*	....do....	89	Commercial wood	....do....	125	-10.0
36	Markwardt *(21)*	Bending	170	Sitka spruce	12 and 17	116	-6.5

[1]USL in percent and T in seconds required to attain the ultimate stress level.

[2]Except for item 20, coefficients were determined by Gerhards from published data.

[3]Based on developing 100 pct stress level in a 5-min static test.

[4]Sitka spruce, Douglas-fir, maple, birch.

[5]Ponderosa and southern pine, red oak, yellow birch, sweetgum.

[6]Average moisture content ranging between 7 and 13 pct and varying by rate of loading.

Considering dry small clear wood specimens only--that is, the solid-line figure 7 curves--rate of loading tends to affect compressive strength (curves 19, 20, 24, and 26) slightly more than bending strength (curves 21, 23, 28, and 36). However, if Keeton's bending data (curve 28) are excluded, the exponential

$$USL = 119 - 7.5 \log T \quad (6)$$

could be used as the representative trend relating percent ultimate stress level to time in seconds for either compressive or bending strength. For small, clear, green wood specimens (curves 22 and 27), the exponential

$$USL = 127 - 10.9 \log T \quad (7)$$

seems a reasonable approximation for relating ultimate stress level in bending to time.

For dry clear wood in shear (curves 26 and 32), ultimate shear stress level is approximately related to time by

$$USL = 116 - 6.5 \log T \quad (8)$$

with a slightly greater rate effect on clear wood in the green condition (curve 25). The rate effect on shear, however, is apparently much lower for wood containing such natural characteristics as knots (curve 33).

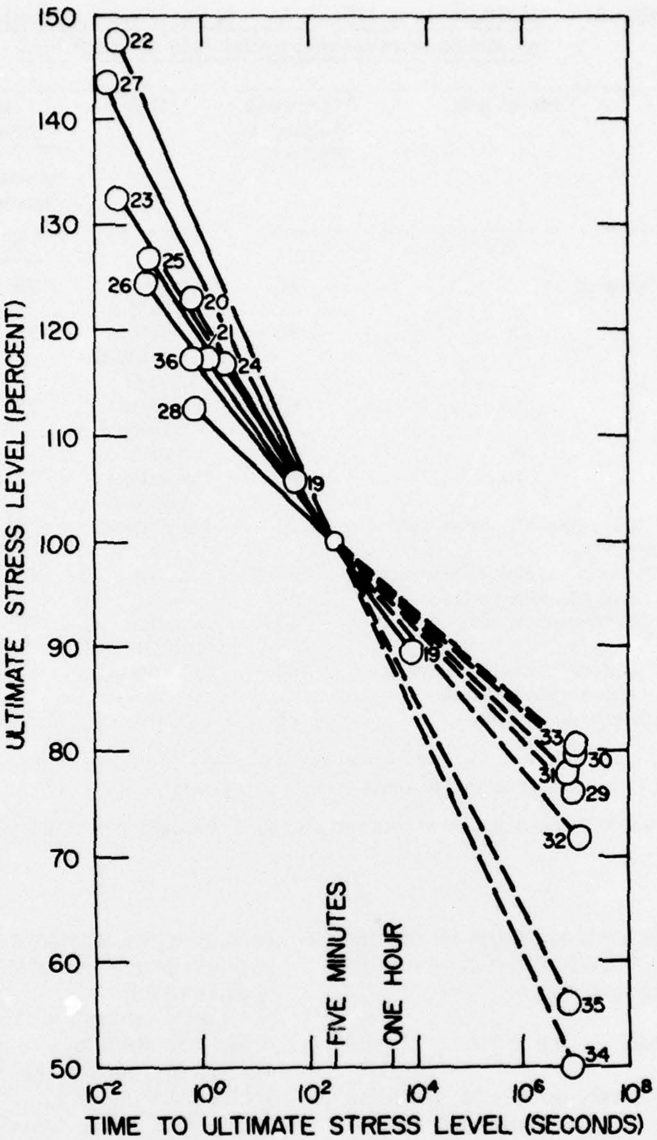

Figure 7.--Typical loading rate relationships for wood--ultimate load versus time to ultimate load. (Numbers refer to itemized data in table 4. For dry wood except where noted.)

19,20,24,26--wood, compression parallel
25--wood, compression parallel, green
26--wood, shear
29,30--lumber, bending
31--lumber, bending, green
21,23,28,36--wood, bending
22,27--wood, bending, green
25--wood, shear, green
32,33--wood tube, shear
34,35--laminated wood, tension perpendicular

(M 143 492)

Table 5. -- Coefficients in USL = M + N log T with related data -- wood-base materials under rate of loading[1,2]

Item No.	Reference No.	Type of test	Approximate number of specimens	Material	Moisture conditioning		Coefficients	
					Temperature	Relative humidity	M	N
					° F	Pct		
H1	Lewis (14)	Bending	40	Insulation board F	75	50	135	-14.1
H2	Lewis (14)	......do......	80	Insulation boards B and D	75	50	122	-8.9
H3	Lewis (14)	......do......	80	Insulation boards A and E	75	50	116	-6.4
H4	Lewis (14)	......do......	40	Insulation board C	75	50	111	-4.4
B3	McNatt (22)	Compression parallel and bending	126	Hardboard	75	64	121	-8.5
B4	McNatt (22)	Tension parallel to surface and edgewise shear	126	......do......	75	64	126	-10.5
B5	McNatt (22)	Interlaminar shear	63	......do......	75	64	117	-7.0
B6	McNatt (23)	Bending	75	Particleboard	75	64	115	-6.2
B7	McNatt (23)	Tension parallel to surface and edgewise shear	150	......do......	75	64	121	-8.5
B8	McNatt (23)	Interlaminar shear	75	......do......	75	64	129	-11.7

[1]USL in percent and T in seconds required to attain ultimate stress level.

[2]Coefficients were determined from published data and are based on developing 100 pct USL in a 5-min static test.

The two curves for tension perpendicular to grain (curves 34 and 35) relate time to ultimate stress level according to

$$USL = 126 - 10.5 \log T \tag{9}$$

for dry wood of relatively large size. Thus the rate effect seems to be more severe for strength perpendicular to grain than for other strength properties of dry wood.

Wood-based Materials

A few studies, besides dealing with the rate-of-loading data for wood, have also dealt with rate of loading effects in insulation board, hardboard, and particleboard. Lewis used relatively rapid loading rates to evaluate the rate effect on bending strength of several types of insulation board *(14)*. McNatt evaluated the effect of loading rate over a broad range including the standard static rate on several strength properties of hardboard and particleboard *(22,23)*.

Lewis' report included data on average times to ultimate stress as well as average moduli of rupture (MOR). In determining M and N coefficients from his results, the average MOR data were regressed on the average times; the regressions were then extrapolated to determine MOR corresponding to a 5-minute test. The regression coefficients were then divided by the 5-minute MOR value to determine the M and N coefficients of equation (4). McNatt, in his two reports, presented regressions of hardboard and particleboard ultimate stress level on time to ultimate. His regressions were then adjusted so that the 100 percent stress level corresponded to the 5-minute test. Results based on the studies of Lewis and McNatt are summarized in table 5.

Equations represented by the coefficients given in table 5 for insulation board suggest a wide range in the effect of loading rate on the bending strength of various types of insulation board. The relative effect of rate does not seem to depend on ultimate strength of insulation board, because the strongest (type E) and the weakest (type A) are represented by the same exponential equation.

As shown by the data in table 5, the effect of loading rate on hardboard and particleboard apparently depends on the strength property involved. Some strength properties, however, are represented by single equations as for tension and edgewise shear. Loading rate has a moderately greater effect on strength of hardboard than strength of particleboard in bending, tension parallel to surface, and edgewise shear. For interlaminar shear, however, loading rate has the greater effect on strength of particleboard.

Equations represented by the coefficients in table 5 are shown in figure 8. The slopes of the curves in figure 8 show a wide range in the effect of loading rate. Two different types of insulation board (type F and type C) account for the extreme range in slopes.

Comparisons of Hardboard and Particleboard With Wood

Comparisons of the data in table 5 with those given earlier for wood suggest that rate of loading has a slightly greater effect on compression, bending, and shear (interlaminar) strength of hardboard than on similar properties of wood. The effect for tension and edgewise shear in hardboard is about the same as that for tension perpendicular in wood. The data also suggest that loading rate affects particleboard slightly less than wood or hardboard in bending strength, particleboard less than hardboard in tensile strength and edgewise shear, and particleboard more than hardboard in interlaminar shear.

COMPARISONS BETWEEN DURATION AND RATE EFFECTS, A DILEMMA

The reader might expect that time to ultimate stess level for ramp loading would be longer than time to failure for constant stress level, given that the ultimate stress level and the constant stress level are equal valued. If so, ultimate stress level should be greater than the constant stress level for equal values of time to failure; in other words, the ultimate stress level curve should lie above the constant stress level curve. This relationship is expected because the ultimate stress level is only attained at the end of ramp loading, whereas the constant stress level is applied over the full duration.

The same principle should apply for the comparison of times for ramp deformation and constant stress. However, the loading rate decreases with time beyond the proportional limit in ramp deformation. Thus, the time to attain the ultimate stress level in ramp deformation should fall between the times for ramp loading and constant loading at the equal-valued stress level. Do the duration of load data and rate of loading data support these expectations?

The bending data for small clear specimens of wood would seem to offer the best chance for answering the question because the data are more extensive for bending than for any other property. Thus the question must be answered between

$$SL = 108 - 5.8 \log_{10} D \text{ in seconds} \quad (5)$$

$$USL = 119 - 7.5 \log_{10} T \text{ in seconds} \quad (6)$$

Note that the equation (5) intercept has been adjusted for duration in seconds to allow easier comparison with equation (6). The contention would not seem to be supported by the two equations representing bending because their slopes are not equal and they have a common stress level at about $4.4(10^6)$ seconds (51 days). The contention would thus seem to be supported only for times less than 51 days where USL is the greater; however, it must be recognized that 51 days is a very long and questionable extrapolation of the data on which equation (6) is based.

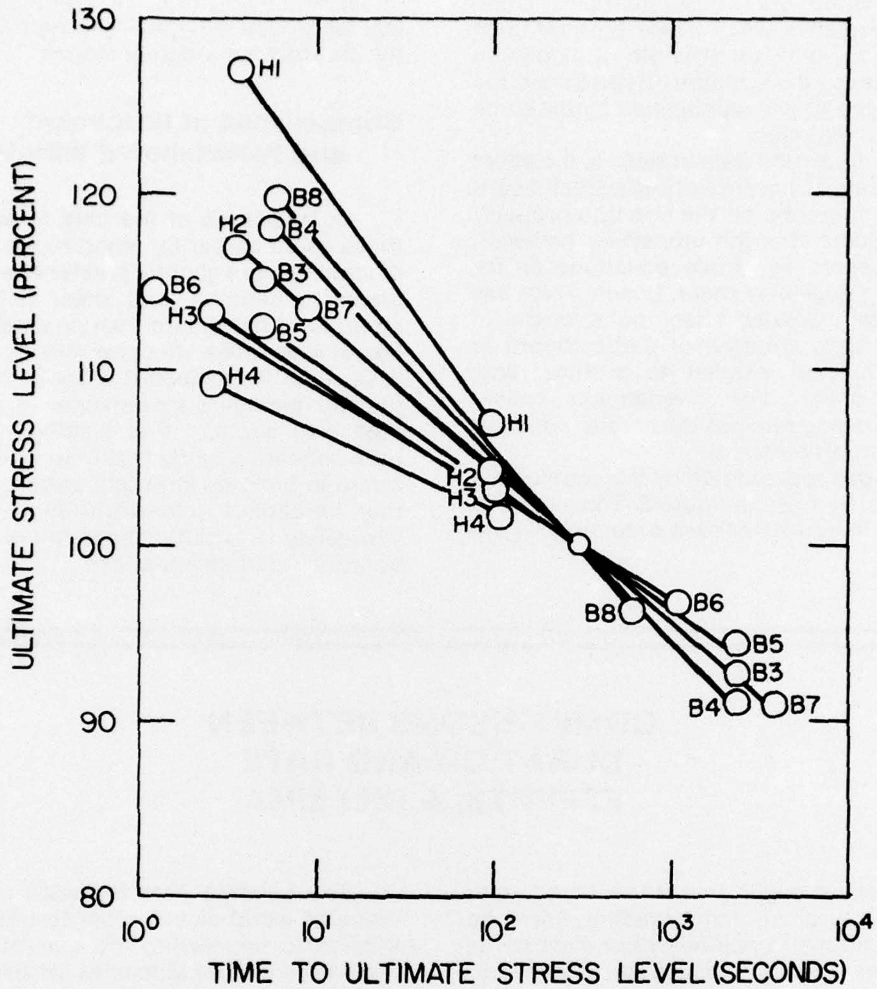

Figure 8.--Typical loading rate relationships for wood-based materials--ultimate load versus time to ultimate load. (Numbers refer to itemized data in table 5.)

H1,H2,H3,H4--insulation board, bending
B3--hardboard, compression, bending
B4--hardboard, tension, edge shear
B5--hardboard, interlaminar shear
B6--particleboard, bending
B7--particleboard, tension
B8--particleboard, interlaminar shear

(M 143 495)

The expected relationship, that ultimate stress level should be greater than constant stress level for equivalent loads, seems to be supported by some other comparisons. The exponential coefficients for Madsen's stepwise bending load data (items 29, 30, and 31 in table 4) imply longer times to failure than predicted by equation (5) over a broad range of stress level. Another example of a favorable comparison over a broad range of stress level exists in some of the compression-parallel-to-grain data (item 4 in table 3 compared with items 19 and 26 in table 4) but unfavorable comparisons can be made, too (item 4 in table 3 compared with items 20 and 24 in table 4).

The relationship expected is not consistently borne out by the wood-based materials data, either. While a favorable comparison exists in the data for particleboard in bending (item B6 in table 5 vs. items E1 and E2 in table 3) and in tension (item B7 in table 5 vs. item B2 in table 3), the expectation is contradicted by the data for hardboard in bending (item B3 in table 5 vs. items C1, C2 and C3 in table 3) and in tension (item B4 in table 5 vs. item B1 in table 3).

The inconsistencies just mentioned do not necessarily prove the expected relationship to be incorrect, because the various comparative results are based on independent studies. The need for a controlled experiment to compare rate and constant loading is apparent.

SUMMARY

Results of the many investigations compared herein suggest:

(1) Duration of load is exponentially related to stress, and ultimate stress is exponentially related to rate of loading.

(2) Shear stress level seems to have a greater effect on the duration of sustained stress for solid wood than either compressive or bending stress level, but the apparently greater effect may be due to a changing environment. When considering the duration of sustained stress in bending, stress level generally has a greater effect on hardboard, particleboard, and plywood than on solid wood.

(3) Rate of loading seems to have a greater effect on strength of green wood than on strength of dry wood, particularly in bending. In dry wood, rate of loading has the greatest effect on strength in tension perpendicular to grain, followed by compression parallel to grain, bending, and shear, although the effects on the last three properties do not differ greatly. Compared to wood, rate of loading in bending has a slightly greater effect on hardboard and a slightly lesser effect on particleboard. Rate of loading in tension and edgewise shear has a greater effect on hardboard than on particleboard, but the effect is opposite in interlaminar shear.

The reader might expect that the time required to attain ultimate stress in ramp loading will be longer than the time to failure under a constant equivalent stress. However, this expectation was not consistently borne out by the reanalyses of the various sets of unrelated data reported in the world literature.

ADDITIONAL RESEARCH NEEDED

Although several studies are reported herein, more research is needed to afford a better understanding of the time-related effects of load on wood properties. One current study nearing completion at Washington State University was set up to evaluate the effect of constant load duration on residual bending strength of small clear wood, particleboard, and plywood specimens. Another study at Washington State University is concerned with constant load durations for lumber in tension. A comprehensive load duration study is being conducted in Canada on structural lumber in bending. These studies should enhance our knowlege about duration of loading.

An ad hoc steering committee on duration of load has proposed more studies on constant- and ramp-loading research that need to be done. The proposed research includes such properties as shear, tension perpendicular to grain, and in particular, tension parallel to grain and bending.[5]

Because realistic structural loads are seldom constant, a theory is needed to relate loading history to residual strength-lifetime for wood. A fully adequate theory should :(1) Relate the effects of loading rate to the effects of constant loading; (2) account for size and quality of wood structural elements and for environmental conditions as well; and (3) account for the effects of alternating loading conditions on cycles or time to failure. Such a theory should be useful in the reliability analysis of wood structures.

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[5]Gerhards, C. C., J. D. Barrett, B. Madsen, M. D. Strickler, and R. Pellerin. Proposed Studies of Time-Related Load Effects on Wood Materials: An Invitation to Participate in Research. For. Prod. J. 26(12): 39 - 40, 1976.

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